Custom Unit Pump Development for the EVA PLSS

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This paper describes the effort by the Texas Engineering Experiment Station (TEES) and Honeywell for NASA to design and test a pre-flight prototype pump for use in the Extra-vehicular activity (EVA) portable life support subsystem (PLSS). Major design decisions were driven by the need to reduce the pump's mass, power, and volume compared to the existing PLSS pump. In addition, the pump must accommodate a much wider range of abnormal conditions than the existing pump, including vapor/gas bubbles and increased pressure drop when employed to cool two suits simultaneously. A positive displacement, external gear type pump was selected because it offers the most compact and highest efficiency solution over the required range of flow rates and pressure drops. An additional benefit of selecting a gear pump design is that it is self priming and capable of ingesting non-condensable gas without becoming "air locked."

The chosen pump design consists of a 28 V DC, brushless, seal-less, permanent magnet motor driven, external gear pump that utilizes a Honeywell development that eliminates the need for magnetic coupling. The pump design was based on existing Honeywell designs, but incorporated features specifically for the PLSS application, including all of the key features of the flight pump.

Testing at TEES verified that the pump meets the design requirements for range of flow rates, pressure drop, power consumption, working fluid temperature, operating time, gas ingestion, and restart capability under both ambient and vacuum conditions. The pump operated at 40 to 240 lbm/hr flow rate, 35 to 100 ^{o}F pump temperature, and 5 to 10 psid pressure rise. Power consumption of the pump controller at the nominal operating point in both ambient and vacuum conditions was 9.5 W, which was less than the 12 W predicted. Gas ingestion capabilities were tested by injecting 100 cc of air into the fluid line; the pump operated normally throughout this test.

I. Introduction

NASA requires an improved portable life support subsystem (PLSS) water pump to support future missions. The current PLSS water pump is a centrifugal multi-vane pump that operates at ~20,200 rpm. This centrifugal pump is sensitive to gas bubbles and can require priming before extravehicular activity (EVA), lengthening EVA

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preparation time. To minimize outgassing and bubble formation during EVA, the current PLSS uses a special pressurizing system that maintains the water loop at 15 psi, via a dedicated 15 psi oxygen regulator that provides backpressure to the feedwater tanks. In addition, the PLSS uses a gas trap and a centrifugal water separator to remove gas from the water loop. Despite these precautions, the current pump has experienced cavitation issues and has shown susceptibility to water impurities.

The current PLSS design goals for the Constellation Space Suit Element require the PLSS pump to use potable water from the vehicle or habitat that has been nominally delivered at 8 psi. NASA also desires to reduce the mass, volume, and power consumption of the pump in order to support longer duration EVAs.

As a result of these goals and the deficiencies of the existing equipment, NASA contracted with TEES to design, build, and test a Custom Unit Pump (CUP) for future use in the PLSS. TEES in turn teamed with Honeywell on the basis of their experience and success with gear pump designs for spaceflight.

The primary requirements for the CUP are derived from JSC-65685, Development Requirements for Waterpump in EVA Technology System (WETS), but are modified for the purpose of development testing. The primary requirement is to provide water flow for thermal regulation to a suited EVA crewmember's Liquid Cooling Garment and to spacesuit components during EVA in vacuum, Lunar, and Martian environments. EVA duration has been set at 8 hours, with an additional 2 hours of pump operation during EVA preparation, leading to a requirement for 10 hours of continuous operation. The design flow rate is 200 lbm/hr (1.5 L/min) at 5 psid water loop pressure drop. The pump must be capable of operating from 40-240 lbm/hr (0.3-1.8 L/min) at 5 psid and must be capable of providing 180 lbm/hr (1.35 L/min) at 10 psid for emergency operations. Operating temperature, defined as the water temperature at the inlet of the pump, ranges from 35 to 100 ^{o}F. The pump must be capable of starting over this entire temperature range. The pump must accommodate water loop pressures at the inlet ranging from 3.3 to 10 psig. The pump may operate in ambient environments, but must be capable of operating in vacuum. Useful life is set at 2000 hours using potable water. Power consumption must not exceed 15 W +/- 10% at 28 VDC at nominal operating conditions. The testing carried out at TEES covered all of the requirements except for useful life, which will be tested at NASA.

II. Pump Design

A. Approach

Our approach was to design an application specific pump that would meet all of the requirements of the flight PLSS Waterpump, then to fabricate a pre-flight prototype that contained the key design features of the flight pump, using existing Honeywell designs that could be fabricated within program budgetary constraints. The features and materials of both flight and prototype pumps are similar, with the prototype modifications resulting in larger size and lower operating speed.

B. Pump Type Selection

Prior work by NASA determined that the PLSS pump must be a positive displacement type, selected for its ability to ingest gas bubbles without becoming "air-locked." There are a number of positive displacement pump types available, ranging from gear pumps and Gerotor pumps to screw and roots pumps, diaphragm pumps, reciprocating pumps, and scroll pumps. Each type has numerous variations. We selected a gear pump, as it offered the most compact and highest efficiency solution. Gear pumps are self priming and capable of ingesting non-condensable gas without becoming "air locked." Honeywell also has considerable experience with gear pumps, having a number of designs that could be modified for this application with minimum effort and cost.

We eliminated Gerotor pumps as we deemed them more complex to fabricate and operate and they provided no performance advantages. We deemed the extra complexity as making it more susceptible to failure from contamination, which is possible in a biological system such as a space suit. We eliminated screw/roots type pumps as they are more suitable for larger applications than this one, and are complex and expensive to fabricate. Various types of diaphragm pumps were eliminated due to their creation of high pressure pulses and concerns over diaphragm fatigue failures. Other types of pumps, such as reciprocating pumps and scroll pumps, were dismissed due to their complexity and cost for this application.

C. Detailed Design

The flight gear pump design uses an application specific pump head and motor design, operating at a nominal speed of 5600 rpm. The prototype pump uses the pump head and housings from a Honeywell Auxiliary Power Unit (APU) fuel pump connected to a motor based on Honeywell's International Space Station Internal Thermal Control System Pump Package Assembly (PPA), with the stator rewound for this voltage. The modified PPA motor fits within the existing APU fuel pump motor housing.

The APU fuel pump was designed for a different flow rate range and pressure rise than the PLSS Waterpump. The gear lobes were lengthened and its nominal operating speed lowered to 3560 rpm in order to meet the specified pressure versus flow rate requirements at the PLSS Waterpump design point.

The gear lobe profiles for both flight and prototype pumps are shaped specifically for a pump application, as opposed to gear profiles designed for power transmission. Many pumps use power transmission gear lobe profiles due to availability and manufacturing cost. These profiles minimize gear wear under high loads and are more efficient for power transmission, but less efficient for pumping. The difference between the two is the clearance or gap at the root of the gears when they are mated. Transmission gear profiles have a greater gap, resulting in a relatively large root volume. Incompressible liquid is trapped in the root volume. This trapped liquid is squeezed between the gears upon mating, increasing the fluid's pressure, and creating forces acting to separate the gears from each other. The energy that goes into increasing the trapped volume's pressure increases power consumption, reducing efficiency. The pump components also have to be larger to handle the side loads generated on the gears.

The peak and root of pump application gears are more closely matched, resulting in small root volumes and little trapped incompressible liquid. The result is lower power consumption, higher efficiency, and smaller pump components.

The pump cartridge end plates were fabricated from Bearium B-10, a bronze based bearing material, and provide the journals for non-contacting hydrodynamic journal bearings for the gear shafts. The gear's side surfaces also contact the B-10 bearing material in order to form better seals, to minimize internal leakage that would bypass the gear set..

D. Motor Design and Controller Selection

The motor operating voltage of 28 V DC was specified by NASA. We selected a two pole, brushless, permanent magnet motor using a sensorless motor control scheme, eliminating the need for Hall Effect rotor position sensors. Sensorless motor control schemes are standard for the current generation of Honeywell pumps for commercial aircraft, and so were deemed a mature and reliable technology. Sensorless motor control requires application specific control algorithms to achieve maximum motor efficiency and is therefore beyond the funding and schedule scope of this program. Low cost commercially available sensorless controllers, such as those used on model airplanes, were designed to operate at lower voltages, and so were deemed not applicable to this design. Therefore, the prototype used conventional Hall Effect rotor position sensors and a commercial Advanced Motion Controls motor controller. Using the Hall Effect sensors gives NASA the flexibility to use a different test rig controller during testing.

The motor stator is cooled by the working fluid. Motor stator heat is conducted from the stator windings, through a stationary metallic fluid barrier, to the fluid side of the barrier, where the working fluid removes the heat by convection. Working fluid is diverted from the high pressure side of the pump cartridge to the motor area for cooling, then exits the motor area via a center passage in the driver gear shaft, and enters the low pressure side of the pump cartridge creating, the flow necessary for convective heat transfer.

The motor rotor is cantilevered off of the driver gear shaft. As a result, no bearings dedicated only to the motor were used.

E. Pump/Motor Coupling

The pump uses a direct shaft to the motor rotor, so no in-line magnetic coupling is used to maintain fluid sealing. A stationary fluid barrier encases the entire pump cartridge and rotor shaft, segregating the working fluid from the stator and Hall Effect sensors. The stationary fluid barrier terminates at the motor end of the assembly using an o-ring seal between the OD of the barrier and the ID of motor housing bore (bore seal). This approach provides semi-hermetic sealing of the working fluid. Magnetic coupling links the stator to the rotor; as in a typical motor, only the magnetic flux passes through the thin metallic fluid barrier. Figure 1 shows the stationary fluid seal within the pump and contrasts our approach with a conventional design.

F. As-built Configuration

During fabrication, some changes were made to the design to reduce cost or schedule. These changes included changing the motor stator lamination material and changing the motor stack bonding process. The lamination material was changed due to a long raw material lead time on the original 0.006 in thick Carpenter 49 nickel iron alloy, which was replaced with a 0.014 in thick M19 silicon iron alloy. The stack bonding process was changed from laser welding to capillary bonding due to a long vendor lead time on the laser weld process.

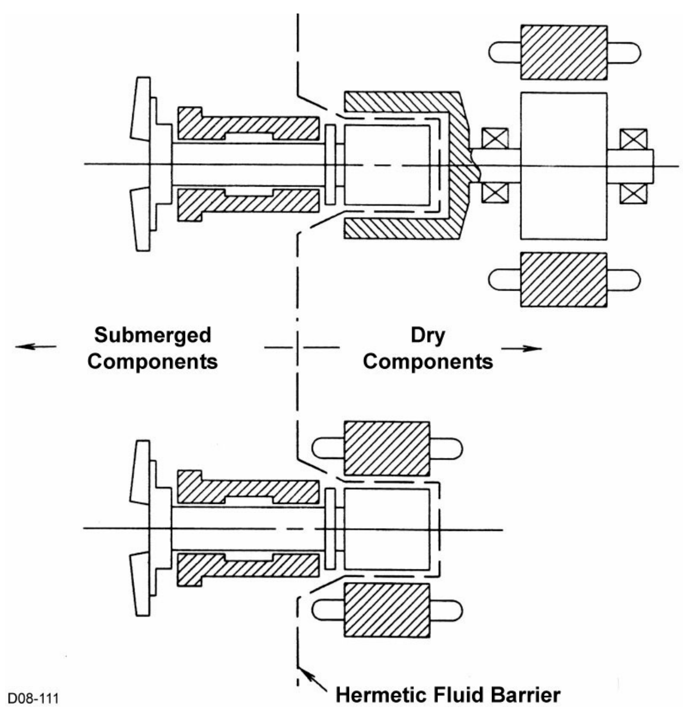

Figure 1. Pump/Motor Coupling (Top figure is conventional magnetically coupled pump. Bottom figure is Honeywell direct drive pump.)

G. Predicted Performance/Characteristics

Table 1 summarizes key pump characteristics for the pre-flight prototype and the flight unit. The main differences between the pre-flight prototype and the flight unit are size, weight, power required, and the motor controller. The power consumption of the pump and motor are expected to be approximately 8 Watts at the design point. We anticipated a significant difference in total power consumption between the pre-flight prototype and the flight unit due to motor controller efficiency. For the pre-flight prototype, we assumed a commercial motor control with an efficiency of 50%, yielding a total predicted power consumption of 16 W at the design point. Actual efficiency of the controller turned out to be 85%, so power consumption at the design point was only 9.5 W The flight unit will use a 90% efficient sensorless motor controller specifically designed for this application, which should reduce the total predicted power consumption to approximately 9 W at the design point.

Table 1. Key Pump Parameter Comparison

Parameter	Pre-flight Prototype	Flight
Design Point Flow, L/min	1.5	1.5
Design Point Delta P, psig	5	5
Design Point Power, W	8 (pump/motor)	8 (pump/motor)
Min. Inlet Press. Reqd., psia	2.6	2.6
Flow Range, L/min	0.3 to 3.0	0.3 to 3.0
Design Speed, rpm	3560	5600
Gear Diameter, inch.	0.72	0.46
Pump Head Max. Diameter,	2.5	1.8
Pump Length, inch	5.9	2.15
Pump Weight, lb	3.1	0.82
Power Type, VDC	28	28
Coupling type	None; one piece rotor	None; one piece rotor
Rotor Position Feedback	Hall effect sensor	Sensorless
Bearings – Motor	None	None
Bearings – Pump	Integral hydrodynamic	Integral hydrodynamic
Gear Material	Stainless Steel	Stainless Steel
Shaft Material	Stainless Steel	Stainless Steel
Gear/Shaft Retention	NA – One piece integral	NA – One piece integral

III. Test Plan and Results

The purpose of the testing was to demonstrate the CUP requirements. From the requirements levied by NASA, we identified the following major testing requirements:

1. *10 hours continuous operation*
2. *Surface temp 35 F to 100 F (also startup at that range of water inlet temperatures)*
3. *Flow rate and differential pressure*
   - *200 lbm/hr (1.5 L/min) at 5 psid (design point)*
   - *180 lbm/hr (1.35 L/min) at 10 psid (emergency)*
   - *Flow rate controllable from 20-120% of nominal (0.3-1.8 L/min) for all conditions*
4. *Inlet water pressure 3.3 – 10 psia*

The independent variables for these tests were water inlet temperature and flow rate. Inlet water pressure was varied over the required range during the test runs. Water loop pressure drop was set to 5 psid for runs 1 through 12 and 10 psid for runs 13 through 15. The dependent variables were power consumption (15 W +/- 10% at 5 psid and 1.5 L/min) and surface temperature of the CUP.

A. Parameter Values

T is inlet water temperature. Q is flow rate. Primary testing occurred with the water loop pressure drop set at 5 psid. Secondary testing occurred with the water loop pressure drop set at 10 psid. Inlet pressure was varied from 3.3 to 10 psia over the set of tests. Testing occurred with the CUP both in ambient air and in vacuum ($P<10^{-4}$ torr). Table 2 defines the values of each level of the main input parameters (temperature and flow rate); 10 psid test flow rates were 90% of these values. Table 3 lays out the test sequence with the loop pressure drop set at 5 psid. Table 4 lists the parameters for the 10 psid test runs.

Table 2. Parameter Level Definitions

Parameter Level	Temperature (^oF)	Flow rate (lbm/hr) <L/min>
1	35	40 <0.3>
2	70	100 <0.75>
3	100	200 <1.5>
4	n/a	240 <1.8>

Table 3. Primary Test Sequence

Run Number	Parameter Values	Duration (hours)
1	T2 Q3	10
2	T3 Q2	2
3	T1 Q1	10
4	T1 Q4	10
5	T2 Q1	2
6	T1 Q2	2
7	T3 Q3	2
8	T2 Q4	10
9	T3 Q1	10
10	T2 Q2	2
11	T1 Q3	2
12	T3 Q4	10

Table 4. High Pressure Drop Test Sequence

Run Number	Parameter Values	Duration (hours)
13	T2 Q3	2
14	T3 Q4	2
15	T1 Q1	2

Data recorded included power consumption of the controller (as input voltage and current), pump inlet and outlet pressure, accumulator pressure, water flow rate, pump surface temperature, and fluid inlet and outlet temperature.

We made two runs beyond those listed above. Run 16 repeated the state point for Run 5, since Run 5 had a 10 minute zero flow condition. Run 17 repeated the state point of Run 1, both to give us a continuous 10 hour test at that state point and to verify performance of the pump following the disassembly, inspection, cleaning, and reassembly that occurred after the first 15 runs were completed.

B. Test Water Loop Layout

Figure 2 is a schematic of the water test loop, showing the piping layout and locations for the instrumentation. The vacuum boundary indicates those parts of the water test loop that were in vacuum; the remainder of the test loop was at ambient conditions. The pressure drop in the water loop was controlled by the setting of the metering valve M1, while pump inlet pressure was controlled by the settings on the eductor attached to the accumulator.

The loop was set to the conditions specified for a particular run using the gear pump, the metering valve, the heating tape, and the cooling coils. Once the test conditions were set, the gear pump was shut off long enough for the water in the loop to stop flowing. The gear pump was then turned on, to demonstrate its ability to start under the full range of environments specified by NASA. The pump inlet pressure varied over time, due to changes in building air supplied to the eductor. We tested the entire range of pump inlet pressures between 3.3 and 10 psia.

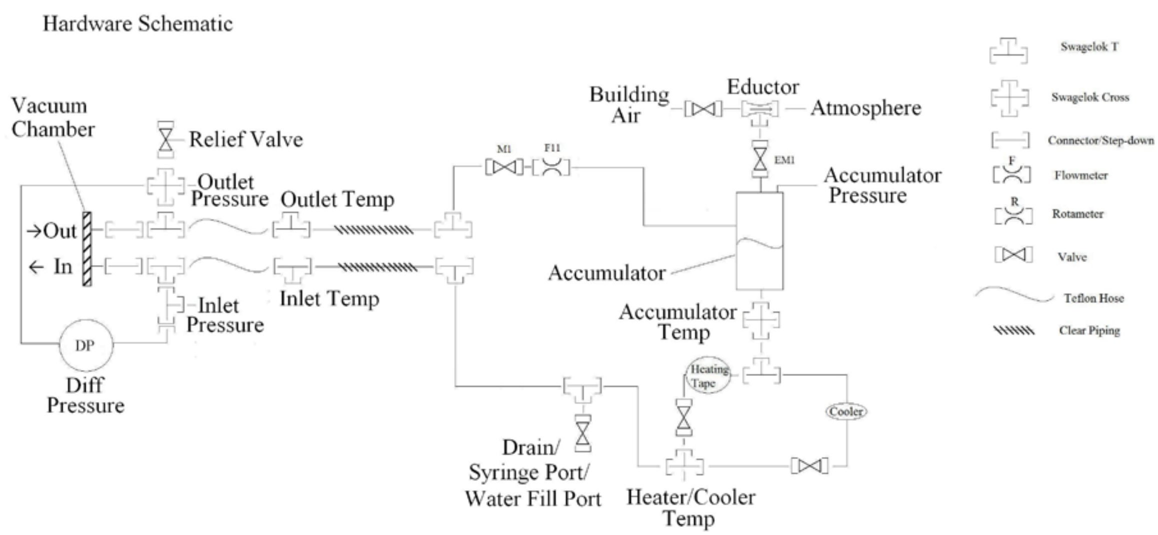

Figure 2. Water Loop Schematic for CUP Testing

C. Test Run Descriptions

Runs 1 through 6, 16, and 17 were performed in atmosphere, to allow easier troubleshooting. The only difference between the runs made in atmosphere and those made in vacuum was the considerable condensation that occurred during the low temperature tests in atmosphere.

Runs 7 through 15 were performed in vacuum at external (to the pump) pressures below 1 x 10^{-4} torr. Power input increased slightly (approximately 0.01 A at 50 V) compared to ambient condition runs; we believe the difference is due to the higher resistance of the controller cable passing through the vacuum chamber feedthroughs.

Runs 1 and 17 were the nominal operating environment for the pump. Runs 3 and 12 were the extreme operating environments. Run 9 was the expected highest temperature condition, due to the minimum fluid cooling of the pump. The other long duration runs were at the highest flow rates, which we thought would be the most stressful condition.

D. Power Consumption

Table 5 shows the power consumption as a function of inlet water temperature and flow rate. Based on our analysis, the contamination of the pump, represented by the time operated, had the largest effect on power consumption. The pump met its design goal of 15 W at nominal conditions by a wide margin.

Table 5. Power consumption as a function of flowrate and water temperature.

Flowrate (L/min)	Temperature (F)		
	35	70	100
0.3	6.8+/-0.8	8.9+/-1.2	9.4+/-0.8
0.75	9.3+/-1.5	9.3+/-1.4	9.0+/-1.1
1.5	16.9+/-1.2	11.8+/-4.2	16.2+/-0.8
1.8	12.7+/-1.6	12.2+/-1.6	18.1+/-4.3

Following Run 16, the pump was shipped back to Honeywell for inspection and cleaning. When the pump was returned to TEES, we reran the state point for Run 1 as Run 17, both to get a continuous 10 hour run at the nominal operating conditions of the pump and to verify that the pump was operating properly following cleaning. Run 17 had a flowrate of 1.5 L/min at 70 F; its power consumption was 9.5 +/-0.1 W, so the cleaning process had a substantial effect on the power consumption of the pump. Figure 3 shows the power consumption for runs 1 and 17 (same state point, pre- and post-cleaning) versus time in the run.

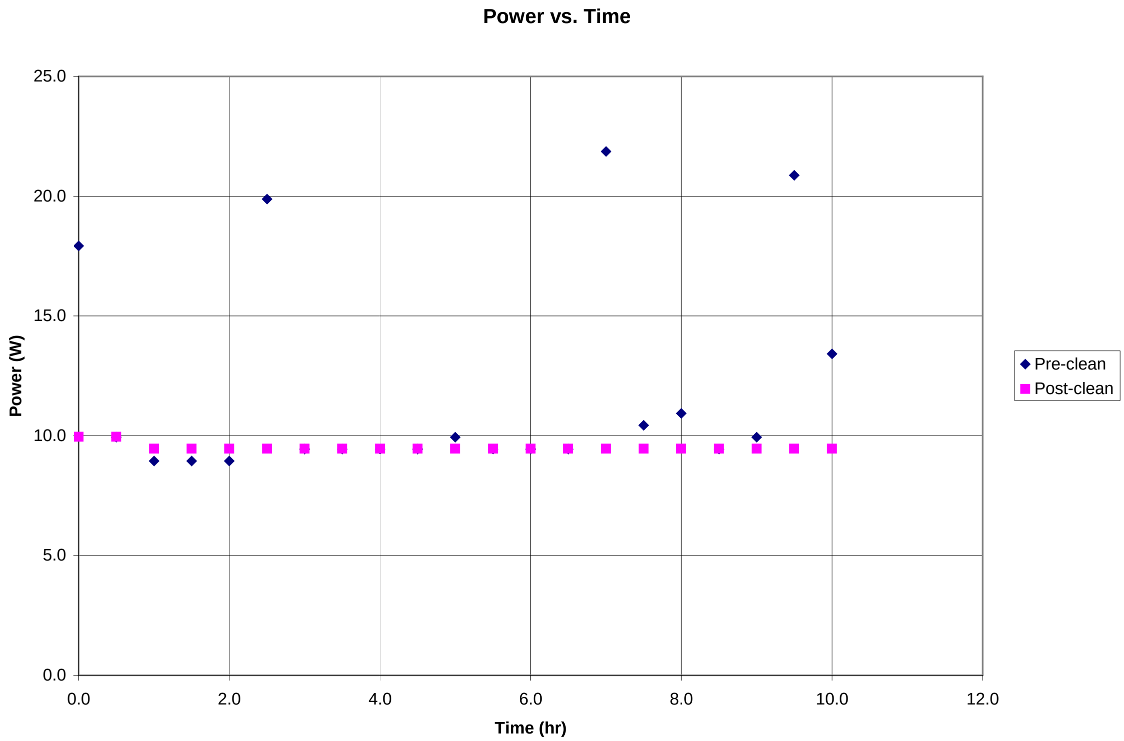

Figure 3. Power consumption of run 1 and run17.

E. Restarts

Per NASA's requirements, we demonstrated that the pump could restart over its entire temperature range. The only difficulties encountered were in the cold restarts, where only 2 out of 5 restarts were successful. In the other 3 cases, the pump restarted after being warmed up slightly (40-45 ^{o}F).

F. Flowrate Versus Head Curves

Following completion of the test plan, we ran a short series of pump curves at 0.75, 1.5, and 1.8 L/min by varying the differential pressure at constant pump speed while increasing differential pressure and at constant flow rate while decreasing differential pressure. We ran a truncated test at 0.3 L/min because the flow was not stable at this flow rate for differential pressures less than 5 psid. We did not run the constant flow rate curve at 1.8 L/min because we were not able to maintain a flow rate of 1.8 L/min at the higher differential pressures. We recorded power input via video camera. All of the curves were run at 70 ^{o}F. Figure 4 is a compilation of the flow rate versus differential pressure data for the pump.

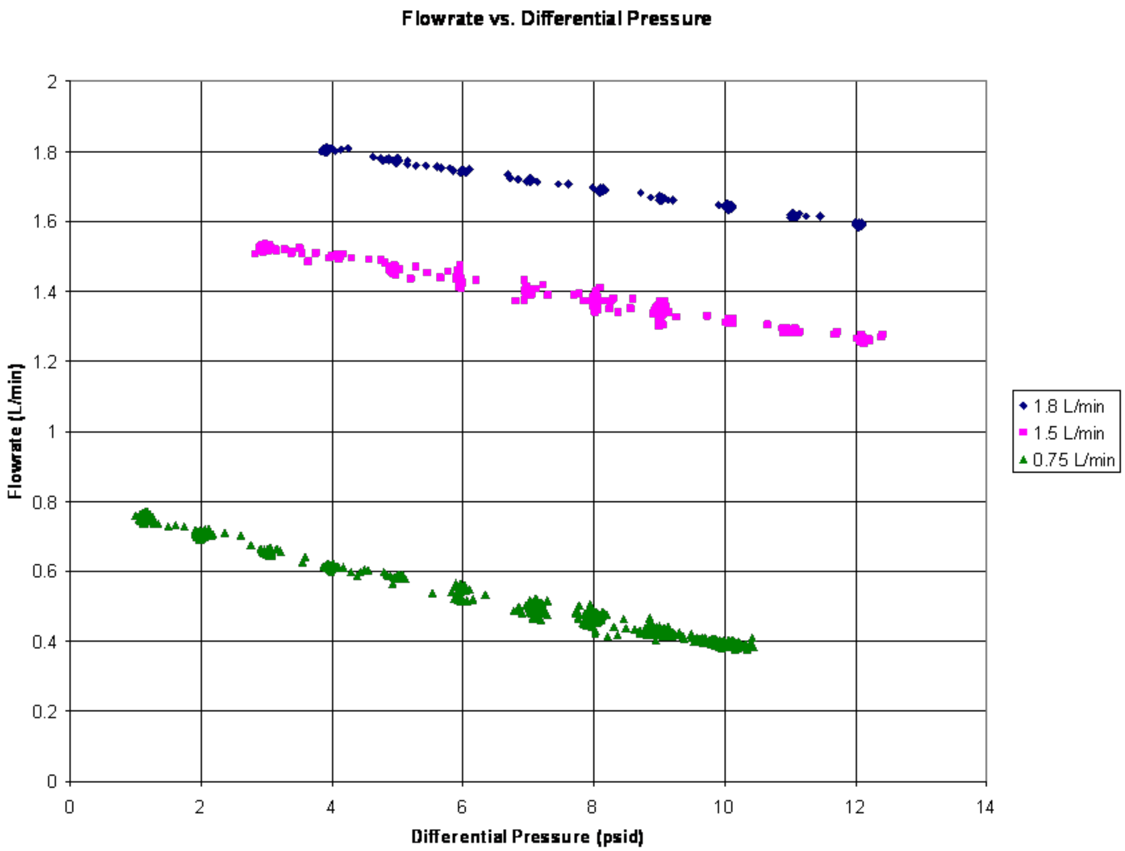

Figure 4. Flow rate versus differential pressure compilation.

G. Bubble/Vapor Testing

We expected vapor and gas bubbles to evolve within the water loop as we lowered the pump inlet pressure and they did. We observed the evolution of these bubbles via the transparent sections in the piping. The size and quantity of these bubbles indicated that the pump's ability to operate is not compromised by ingesting small amounts of small bubbles.

Because of the power anomalies and unexpected shutdowns encountered during testing, we decided to add a bubble injection test to the plan. We attached a cylinder containing approximately 100 mL of air to an inlet port on the flow loop. While running at steady state at 1.5 L/min, 70 ^{o}F, and 5 psid across the pump, we opened the valve to the cylinder, injecting the 100 mL into the pump in about 1.5 seconds. The air flowed through the loop and the pump. Figures 5 and 6 show the data traces for the two bubble injection tests we ran. The pump returned to normal operation without operator intervention following each of the tests. Based on the results of these tests, we believe some of the power excursions observed in other runs may have been cavitation events.

While not definitive, this bubble ingestion testing establishes the basic ability of the pump to operate through gas ingestion, one of NASA's goals for the CUP.

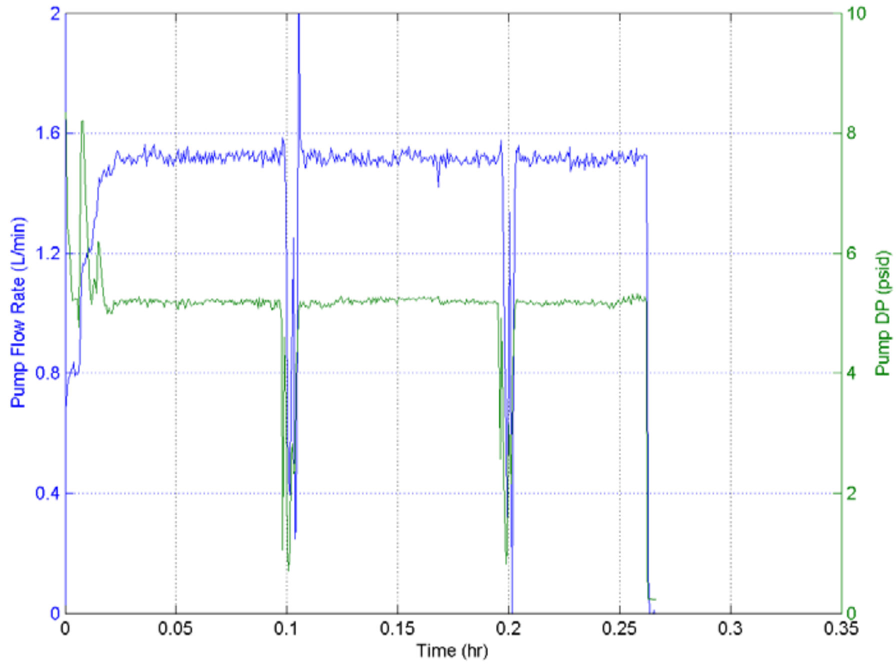

Figure 5. Flow rate and differential pressure versus time, gas ingestion test.

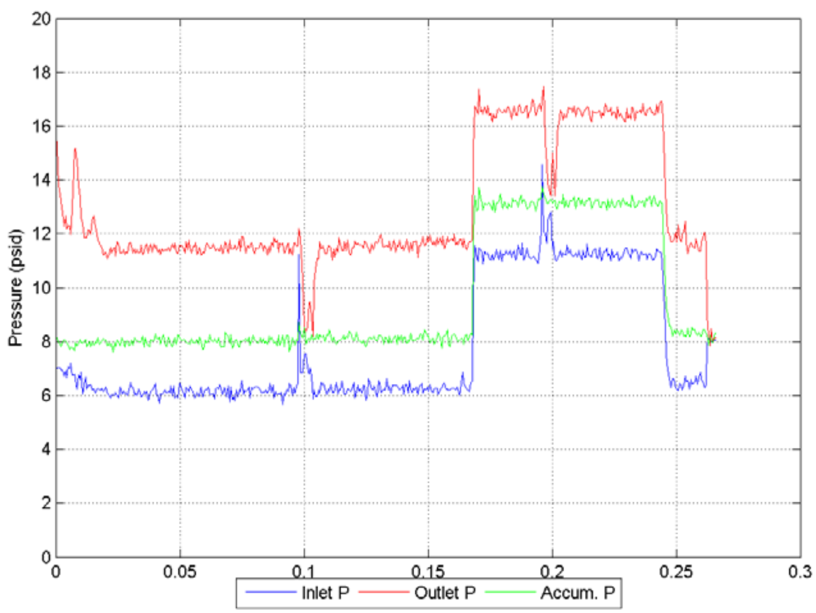

Figure 6. Pressures versus time, gas ingestion test.

H. Post Test Examination

Following the completion of run 16, the CUP was returned to Honeywell for disassembly, inspection, and cleaning. Gray contaminant material was removed from inside the pump. Light scoring occurred on the pump cartridge assembly and gear sets. This scoring is due to the gray contaminant material. Rub marks on the rotor and bore seal were caused by contact between the rotor and the bore seal during operation and may have been responsible for the longer duration power excursions noted in several runs.

Following cleaning and reassembly, the CUP was returned to TEES. We then performed run 17 at the normal operating conditions. Completion of this run verified that the pump was operating as before. There were no power excursions during run 17 and the pump and controller only consumed 9.5 W at this state point.

I. Results Summary

TEES and Honeywell have designed and built a compact, efficient pump suitable for use in the Constellation Space Suit PLSS and future space suits (Figure 7). We tested the pump over the range of operational conditions it will encounter in use in a vacuum environment. By demonstrating that power consumption and pump parameters remained within the allowable limits over the entire range of testing, we demonstrated that the CUP meets the requirements of the project.

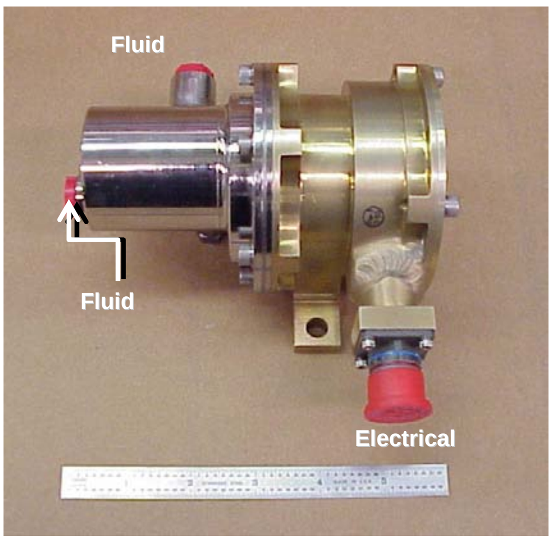

Figure 7. TEES/Honeywell Custom Unit Pump

The CUP experienced 9 anomalies during testing, 3 of which involved flow stoppage and power fluctuations, and 6 of which involved only power fluctuations. In runs 3 and 5 there was some evidence of flow instability at low flow rates during startup (pulsing flow behavior). In all cases of flow stoppage, the pump either restarted on its own, or restarted when the operators commanded it to do so. There were three instances at low temperature when it took several attempts before the pump restarted. There were no instances where multiple restarts were required at 70 ^{o}F or 100 ^{o}F. In all cases involving only power fluctuations, all other pump parameters were unchanged.

Table 21 summarizes the performance of the CUP against its requirements.

Table 21. Compliance Verification Matrix

Requirement	*How Design Meets Requirement*
Operating time 10 hours continuous	Experimentally demonstrated, runs 1, 3, 4, 8, 9, 12
Surface Temperature 35 F to 100 F	Experimentally demonstrated, runs 1-15
Flow rate 200 lbm/hr at 5 psid	Experimentally demonstrated, runs 1, 7, 11
Flow rate 180 lbm/hr at 10 psid	Experimentally demonstrated, run 13
Inlet Water pressure 3.3-10 psi in vacuum EVA environment	Experimentally demonstrated, runs 1-15
Useful Life 2000 hours	To be demonstrated at JSC
Water quality	To be demonstrated at JSC
External operating environment	Demonstrated operation in ambient (runs 1-6) and vacuum (runs 7-15) environments
Startup capability - 17 out of 17 startups successful - 5 out of 8 restarts successful	Demonstrated startup at temperatures ranging from 35 ^{o}F to 100 ^{o}F, runs 1, 5, 6, 12, 15; 2 out of 5 cold restarts were successful
Motor type	Permanent magnet
Overall power consumption 15+/-10% W	Experimentally demonstrated, runs 1, 7, 11
Supply Voltage 28 VDC	21-24 VDC delivered to pump motor phases
Speed Control 20%-120% of flow	Experimentally demonstrated, runs 1-15

IV. Conclusions

Designed, built and tested for NASA's future long duration EVA's, the TEES custom unit pump demonstrated its major requirements and goals as follows:

The pump operated at all of the prescribed flow rates, differential pressures, inlet pressures, and temperatures.

The power consumption of the pump was below the required maximum value.

The pump restarted at temperatures of 35 ^oF, 70 ^oF, and 100 ^oF.

The CUP exhibited very stable, repeatable operation over the entire range of test conditions examined.

The CUP was able to ingest large quantities of air and return to stable operation at its previous settings.

The commercial motor controller operated at approximately 85% efficiency during testing.

A general recommendation for a flight design is to provide special attention to the low flow and low temperature operation of the pump during the flight design and testing phases.

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